

Large scale jets in AGN: multiwavelength mapping

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ABSTRACT

High energy (X-ray) emission from large scale extragalactic jets is likely to be due to inverse Compton scattering of relativistic particles off the photons from both the cosmic microwave background field and the blazar nucleus. The first process dominates the observed high energy emission of large scale jets if the plasma is moving at highly relativistic speeds and if the jet is aligned with the line of sight, i.e. in powerful flat radio spectrum quasars. The second process is relevant when the plasma is moving at mildly bulk relativistic speeds, and can dominate the high energy emission in misaligned sources, i.e. in radio-galaxies. We show that this scenario satisfactorily accounts for the spectral energy distribution detected by *Chandra* from the jet and core of PKS 0637–752.

Key words: galaxies: active - galaxies: jets - galaxies: quasars: individual: PKS 0637–752 - radiation mechanisms: non thermal

1 INTRODUCTION

The *Chandra* X-ray Observatory (CXO) is providing us with unprecedented high spatial (and spectral) resolution data on extended structures. The very first observation of a radio-loud quasar, PKS 0637–752, revealed the presence of an X-ray jet extending for ~ 10 arcsec (Chartas et al. 2000; Schwartz et al. 2000), and since then other X-ray jets have been detected with high spatial resolution (Cen A, Pictor A, see CXO www page <http://chandra.harvard.edu/photo/cycle1.html>).

While the detection of an X-ray jet is not unprecedented (e.g. M87, Biretta, Stern & Harris, 1991; 3C273, Harris & Stern 1987; Röser et al. 2000), it is interesting to notice that both radio-galaxies and blazar-like sources (i.e. with a jet oriented close to the line of sight) have been observed. Models involving inverse Compton scattering of the Cosmic Microwave Background (CMB) and nuclear hidden quasar radiation to produce large scale X-rays have been proposed (e.g. Brunetti, Setti & Comastri 1997). However it has been found that the local broad band spectral energy distributions from the knots in both PKS 0637–752 and M87, are not straightforward to interpret, since the level of the X-ray emission is higher than what simple models predicts (e.g. Chartas et al. 2000; Schwartz et al. 2000, Röser et al. 2000).

In this Letter we propose a general scenario involving both highly and mildly relativistically moving plasma in the jet and consider the dominant radiation fields on which relativistic particles can Compton scatter (Section 2). This can naturally and satisfactorily account for enhanced large scale

X-ray emission in all jetted sources, both blazars and radio-galaxies. We also consider the spatial distribution of emission at different frequencies (Section 3). The predictions are compared to the results on PKS 0637–752 in Section 4 and our conclusions drawn in Section 5.

2 MIRRORS IN THE JET

Comparatively little is observationally known on the structure and dynamics of extragalactic jets. Theoretically one would expect the existence of a velocity structure along the jet, from a faster inner core to slower outer regions of the flow – dissipation can be produced by shocks in the relativistic plasma flow, or deceleration of the jet material can be caused by obstacles in the jet or by the interaction of the relativistic flow with the (steady) walls. However only recently observational evidence has been accumulating in support of such possibility and on the relevant role of the outer layers in contributing to the observed emission. This evidence includes the morphology and polarization structure of large scale low power jets (Komissarov 1990, Laing 1993, 1999; Giovannini et al. 1999) as well as apparent inconsistencies on the value of the relativistic beaming parameters as inferred from the flux observed at large angles with the jet direction and the statistic properties of beamed and parent populations according to the unification schemes (Chiaberge et al. 2000). These facts have been satisfactorily accounted for by schematically consider the jet as constituted by two main components: a slow, but still mildly relativistic, outer

“layer” and a high relativistically moving “spine”. Strong support for such a fast component even at large (arcsec) distances from the active nucleus comes from the detected superluminal motion of M87 on kpc scales (Biretta, Sparks & Macchetto 1999).

Within this assumption on the jet structure, let us consider the electromagnetic fields (magnetic and radiative) which can contribute to the emission of relativistic electrons at different distances along the jet, and thus determine the corresponding dominant cooling process for relativistic particles. Indeed, if dissipation occurs in knots at large distances, the accelerated particles can cool by the synchrotron and synchrotron self-Compton (SSC) processes, but also by scattering any radiation produced externally to the knot itself. The relative importance of the fields clearly depends on the bulk Lorentz factor of the emitting regions in the jet, i.e. the spine and the layer bulk Lorentz factors.

2.1 The radiation field produced by the nucleus

Theoretical advances in recent years (especially due to high energy γ -ray observations) have convinced us that the bulk of the emission seen in blazars is produced in a rather well defined region of the jet, which on one hand cannot be too compact (hence, close to the jet apex) in order not to absorb γ -ray photons through γ - γ interactions, and on the other hand cannot be too large in order to vary on short timescales (Ghisellini & Madau 1996). This region should be located at some hundreds of Schwarzschild radii from the black hole, and produce radiation collimated in the beaming cone of semi-aperture angle $\sim 1/\Gamma_{\text{in}}$, where Γ_{in} is its bulk Lorentz factor. At larger distances, the jet is therefore illuminated by this radiation: it turns out that it can be observationally relevant as scattered radiation if the large scale plasma has only mildly relativistic speeds, as supposed for the jet layer.

In fact, let us assume that on the parsec and sub-parsec scale the jet contains a blazar-like emitting region, moving with a bulk Lorentz factor Γ_{in} at an angle θ with the line of sight. This region emits an intrinsic (comoving) synchrotron luminosity $L'_{\text{s,in}}$.

Further out, at a distance z from the jet apex, there is a knot where dissipation occurs and electrons are accelerated and therefore radiate. If the bulk Lorentz factor Γ_{out} of this region is significantly smaller than Γ_{in} this region will see the nuclear (inner) flux enhanced by beaming, with a corresponding radiation energy density

$$U'_{\text{in}} \sim \frac{L_{\text{s,in}}}{4\pi z^2 c \delta_{\text{in}}^4} \frac{\Gamma_{\text{in}}^2}{\Gamma_{\text{out}}^2} \quad (1)$$

where $\delta_{\text{in}} \equiv \Gamma_{\text{in}}^{-1} [1 - \beta_{\text{in}} \cos(\theta)]^{-1}$ is the beaming or Doppler factor of the inner jet, and $\beta_{\text{in}} c$ is the corresponding velocity.

2.2 The comoving fields

This external energy density must be compared with the local magnetic (U'_B) and synchrotron radiation (U'_{out}) energy densities. If the magnetic field is in equipartition with the locally produced synchrotron radiation, we have $U'_B \sim U'_{\text{out}}$, and the self-Compton emission is then of the same order.

Alternatively, the field can be estimated by conservation of magnetic flux L_B , which at large distances gives

$$U'_B = \frac{L_B}{\pi \psi^2 z^2 c \Gamma_{\text{out}}^2}, \quad (2)$$

where we have assumed a conical jet of semiaperture angle ψ . The synchrotron energy density can be written as

$$U'_{\text{out}} = \frac{L_{\text{s,out}}}{4\pi \psi^2 z^2 c \delta_{\text{out}}^4}. \quad (3)$$

The knot is assumed for simplicity to be a cylinder of radius $R = \psi z$ and width $\Delta R' = R$. δ_{out} is the beaming factor of the knot radiation.

2.3 The quasi-isotropic fields

Further photon fields which can provide seed photons for Compton scattering are those reprocessed in the Narrow Line Region (NLR) and by any large scale dust structure surrounding the nucleus. We consider these two components as produced within \sim kpc scale and therefore they would be seen de-amplified by plasma moving along the jet on larger scales:

$$U'_{\text{kpc}} \sim U'_{\text{NLR}} + U'_{\text{dust}} \sim \frac{f L_{\text{disk}} + a T_{\text{dust}}^4}{4\pi z^2 c \Gamma_{\text{out}}^2}, \quad (4)$$

where $f L_{\text{disk}}$ is the fraction of the inner isotropic emission which is reprocessed by the NLR and the dust is assumed to re-emit as a quasi-blackbody at temperature T_{dust} .

Finally, the CMB radiation provides a uniformly distributed contribution to the radiation fields:

$$U'_{\text{CMB}} \sim a T_{\text{CMB}}^4 (1+z)^4 \Gamma_{\text{out}}^2. \quad (5)$$

The inverse Compton process on the CMB photons is particularly relevant if the knot is moving relativistically, since in this case the CMB energy density as seen in the comoving frame is amplified by Γ_{out}^2 .

Any stellar contribution is assumed to be of the order of or smaller than the CMB contribution on all scales and is therefore neglected here. However, since this component provides seed photons at higher frequencies than the CMB, it can become important for the Compton emission at the largest (γ -rays) energies.

Another possible contribution to the seed photons comes from the interplay between the spine and the layer of the jet, if both are active and relatively close. Radiation produced in one zone can in fact be seen amplified (by beaming) by the other zone. We have however verified that these contributions are less important than the other ones, at least for the range of parameters considered in this work.

2.4 The relevant fields

The relative importance of the radiation produced by the blazar component and the local SSC emission is given by

$$\frac{U'_{\text{in}}}{U'_{\text{out}}} = \frac{(\psi \Gamma_{\text{in}})^2}{\Gamma_{\text{out}}^2} \frac{L_{\text{s,in}}}{L_{\text{s,out}}} \left(\frac{\delta_{\text{out}}}{\delta_{\text{in}}} \right)^4 = \frac{(\psi \Gamma_{\text{in}})^2}{\Gamma_{\text{out}}^2} \frac{L'_{\text{s,in}}}{L'_{\text{s,out}}}. \quad (6)$$

For illustration, consider the two cases of $\Gamma_{\text{out}} = \Gamma_{\text{in}}$ (corresponding to a fast moving spine) and $\Gamma_{\text{out}} \sim 1$ (corresponding to a layer at rest relative to the center):

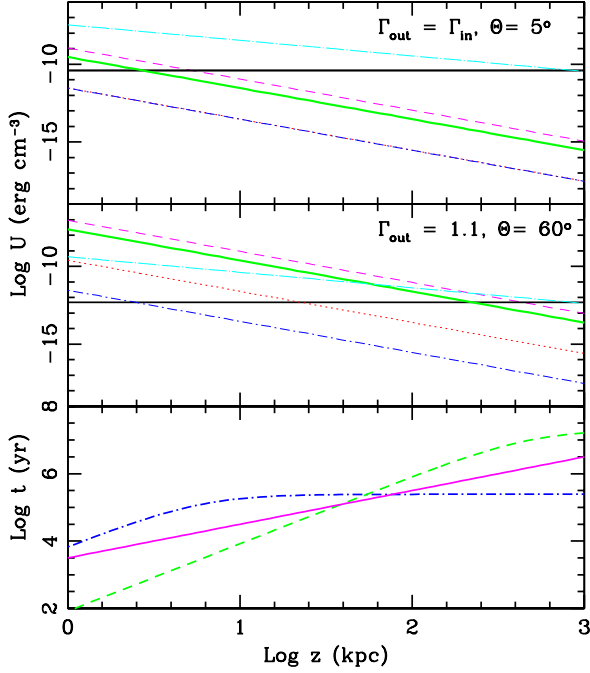


Figure 1. Energy densities as a function of z for a highly relativistic knot ($\Gamma_{\text{out}} = \Gamma_{\text{in}} \sim 10$) (*upper panel*) and a mildly relativistic one ($\Gamma_{\text{out}} \sim 1.1$) (*middle panel*). We consider these two components to dominate at small and large observing angles, respectively. The various fields are represented as: U_{in} (solid, oblique line), U_{B} (dashed), U_{kpc} (dotted), $U_{\text{s,out}}$ (dot-dashed), U_{CMB} (solid, horizontal). Intrinsic luminosities $L_{\text{in}} \sim 10^{43}$, $L_{\text{s,out}} \sim 10^{42}$ and $L_{\text{B}} \sim 10^{45}$ erg s $^{-1}$ have been assumed. The particle distribution is assumed to be a power law of slope $p=2.5$ between $\gamma_{\text{max}} \sim 10^5$ and $\gamma_{\text{min}} \sim 10$, with a corresponding energy density U_{e} (dot-long-dash line). The *bottom panel* shows the radiative cooling timescales (dash-dot line for the spine and dashed for the layer) compared with the timescale for adiabatic losses (solid), calculated as $t_{\text{ad}} = 0.1z/c$.

i) $\Gamma_{\text{out}} = \Gamma_{\text{in}}$: in this case U'_{in} dominates if $L_{\text{s,in}} > L_{\text{s,out}}/\psi^2$, i.e. if the observed power coming from the nucleus is two orders of magnitude (for $\psi \sim 0.1$) greater than the power of the knot;

ii) $\Gamma_{\text{out}} \sim 1$: in this case, for $\psi\Gamma_{\text{in}}$ of the order of unity, U'_{in} dominates if the power dissipated in the inner jet is greater than the power dissipated at large scales, i.e. if $L'_{\text{s,in}} > L'_{\text{s,out}}$.

We conclude that it is likely that some part of the outer jet can produce – depending on the relative velocities of the inner and outer regions – an inverse Compton spectrum dominated by seed photons coming from the inner regions, for $L_{\text{s,in}} > 10^2\text{--}10^4 L_{\text{s,out}}$.

In order to fully compare all the contributions discussed above to the Compton emission of the knot, in Fig. 2 we report the relevant energy densities as a function of the distance along the jet, for two values of the bulk Lorentz factors (schematically corresponding to a “spine” and “layer”).

It is clear from Fig. 2 that along most of the jet the CMB is the dominant field for the spine: the energy densities of the magnetic field and of the nuclear blazar emission becomes relatively important only in the inner parts ($< \text{few kpc}$).

On the contrary for a slowly moving layer the beamed inner radiation can dominate the radiation energy density up to extremely large scales. Reprocessed radiation from the NLR and dust structures do not provide a relevant contribution at any distance.

Furthermore, for the spine emission, a systematic increase of the Compton dominance (ratio of the luminosity in the high energy and low energy spectral components) is expected with increasing distance. Clearly in terms of the observed luminosity the relative contributions of the spine and layer have to be weighted by the corresponding beaming factors.

2.5 Particle energy density

Finally, let us consider the relative importance of the energy density in relativistic electrons and fields (see Fig. 1). The electron density can be estimated from the intrinsic synchrotron luminosity $L'_s = L_s/\delta_{\text{out}}^4$ of the knot:

$$n'_e = \frac{3L'_{\text{s,out}}}{4\pi R^3 c \sigma_T U'_B \langle \gamma^2 \rangle} \quad (7)$$

and therefore the electron energy density $U'_e = n'_e \langle \gamma \rangle m_e c^2$ can be written as

$$U'_e = 1.2 \times 10^{-2} \frac{U'_{\text{out}}}{U'_B} \frac{3-p}{p-2} \frac{(\gamma_2/\gamma_1)^{p-2}}{\psi^{-1} z_{\text{kpc}}^{-1} \gamma_2} \text{ erg cm}^{-3} \quad (8)$$

where we have assumed that the particle distribution is a power law, $N(\gamma) \propto \gamma^{-p}$, between γ_1 and γ_2 , with $2 < p < 3$. For illustration, assume $p = 2.5$, $\gamma_1 = 10$, $\gamma_2 = 10^5$, and equal synchrotron and magnetic energy densities. In this case $U'_e \sim 1.2 \times 10^{-5} \psi_{-1}^{-1} z_{\text{kpc}}^{-1}$ erg cm $^{-3}$. It is then clear that if $U'_B \sim U'_{\text{out}}$ holds, then the energy density of relativistic electrons is bound to dominate by a large factor, especially at large distances (since U'_e scales as z^{-1} while the other energy densities scale as z^{-2}).

The only way to decrease the particle dominance is to increase the relative importance of U'_B . But this immediately implies that the SSC component of the spectrum becomes weaker than the synchrotron one. If a large Compton X-ray flux is instead observed, then a more moderate particle dominance can be achieved only if this emission is not due to SSC. Equipartition between particles and magnetic field is however possible if the external radiation fields are orders of magnitude greater than the local synchrotron energy density (if the X-ray flux is comparable to the low energy synchrotron one). Such large ratios of external to local radiation fields are possible for the spine component (see Fig. 1) at large distances. The spine component of jets can then have a Compton dominated spectrum even in the case of equipartition between magnetic field and particles, providing that the magnetic field in the emitting region is greater than the values shown in Fig. 1 (possibly due to shock compression and field amplification).

In summary, suppose to observe a significant inverse Compton X-ray flux in an extended jet structure. If the source is a radio-galaxy, we have a strongly particle dominated emitting region, since we are likely observing the emission from the layer, for which the external photon fields can only slightly reduce the particle to magnetic energy density ratio. If the source is an extended jet of a blazar, we are observing the emission from the spine, with a strongly

dominating CMB field. In this case equipartition between magnetic field and particle is possible (even if not guaranteed).

3 MULTIFREQUENCY MAPPING

In aligned sources (i.e. superluminal sources and blazars) the more visible parts of the jet will be those still moving at relativistic speeds, producing radiation highly beamed towards the observer (i.e. the spine emission will dominate). On the contrary, in misaligned radio-galaxies the slower moving parts (layer) dominate with quasi-isotropic radiation providing most of the observed flux.

A further crucial point to be considered in such extended structures is the relative role of radiative versus adiabatic cooling. The bottom panel of Fig. 1 shows the radiative cooling timescales of electrons with $\gamma = 10^5$ of both the spine and the layer.

Due to the different radiation fields dominating in the spine and in the layer, the spine is radiatively efficient in the outer parts and the layer in the inner parts. Therefore at large distances the adiabatic losses are negligible for the spine, and are instead important for the layer.

In Fig. 2 we show examples of the broad band energy distribution for the spine and layer, where the corresponding jets are assumed to be observed at 5 and 60 degrees from the jet axis, respectively. The particle distribution is normalized in such a way to give a fixed amount of *total* luminosity (i.e. synchrotron plus Compton). The addition of the external radiation field then changes also the synchrotron flux level, and greatly changes the Compton to synchrotron flux ratio. This can be seen in the upper panel of Fig. 2, comparing the SED corresponding to SSC only and the SED including the contribution of the external photons coming from the nucleus. Note that the pure SSC case can be appropriate for a curved or bent jet, in which the beamed radiation from the center does not illuminate the large scale jet.

A further prediction of the model due to the energy dependent cooling timescales is that the relative extension from the dissipation region where particle are accelerated would be larger for slower cooling particles, i.e. will depend on the mapping frequency, as $\propto ct_{\text{cool}}(1+z)\Gamma^{-1}$.

4 THE JET OF PKS 0637-752

Let us then quantitatively consider the specific case of the jet associated with PKS 0637-752, and in particular of its knot W7.8, for which detailed information are reported (Chartas et al. 2000).

The spatially resolved spectral analysis allowed to identify knots of emission similar in structure and intensity to those seen in the radio (Tingay et al. 1998) and optical (HST; Schwartz et al. 2000) bands. According to the CXO and radio results, the source can be resolved at 5 GHz with a dimension of $0.3''$, at a distance from the central source of about $7.8''$, leading to an upper limit on $\psi < 0.04$.

VSOP observations detected apparent superluminal motion in the (pc scale) jet (Lovell 2000), setting a lower limit on the (inner) bulk Lorentz factor $\Gamma > 17.5$ and an upper limit on the viewing angle $\theta < 6.4$ degrees (assuming

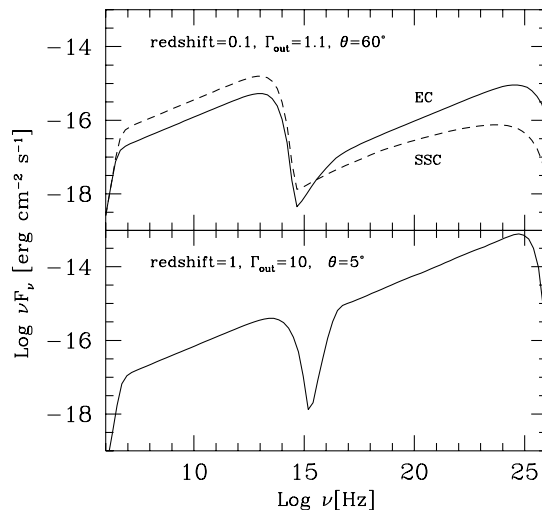


Figure 2. SED calculated assuming that at distances of 10 kpc from the center a region of 1 kpc of size embedded in magnetic field of 10^{-5} G radiates an intrinsic power of 3×10^{41} erg s $^{-1}$. The nuclear (blazar) component emits an intrinsic power of 10^{43} erg s $^{-1}$. A power law electron distribution of slope $p = 2.5$ between $\gamma_1 = 30$ and $\gamma_2 = 10^6$ has been assumed. The *upper panel* shows the case of the emission from a layer moving with $\Gamma_{\text{out}} = 1.1$ at a viewing angle $\theta = 60^\circ$. The dashed line corresponds to the SED assuming that electrons emit SSC radiation only. The solid line takes into account the radiation field, coming from the nucleus, illuminating the region. The *bottom panel* shows the emission from a spine moving with $\Gamma_{\text{out}} = \Gamma_{\text{in}} = 10$ at a viewing angle $\theta = 5^\circ$. We have assumed a redshift equal to 0.1 for the layer and equal to 1 for the spine, in order to have comparable observed fluxes.

$H_0 = 50$ km s $^{-1}$ Mpc $^{-1}$ and $q_0 = 0$). The small scale jet appears to be well aligned with the kpc scale one.

As discussed by Chartas et al. and Schwartz et al., the radio spectrum can be explained as synchrotron emission, as also supported by the detection of strong linear radio polarization, while the X-ray emission largely (~ 2 orders of magnitude) exceeds the extrapolation from the radio-optical spectrum. On the other hand, if the X-ray intensity is interpreted in terms of SSC emission large deviation from equipartition between magnetic field and particle energy density and/or strong inhomogeneities have to be invoked in the emitting region. Thermal emission by e.g. shocked plasma also appears to be unlikely, as it would imply high particle density and thus unobserved large rotation measures. On the contrary in the proposed scenario the X-ray emission can be satisfactorily interpreted as scattered CMB radiation.

Fig. 3 shows the broad band spectral energy distributions of both the nuclear blazar component and of the knot W7.8. To fit the core emission, we have assumed an emitting region of size $R = 9 \times 10^{16}$ cm, magnetic field $B = 4$ Gauss, bulk Lorentz factor $\Gamma_{\text{in}} = 17$ and viewing angle $\theta = 6^\circ$ (corresponding to $\delta_{\text{in}} = 8.2$). The emitted intrinsic luminosity is $L' = 8 \times 10^{43}$ erg s $^{-1}$. For this nuclear jet component we could estimate the kinetic power carried by the jet: in the form of Poynting flux and emitting electrons we have respectively $L_B = 1.4 \times 10^{46}$ erg s $^{-1}$ $L_e = 1.4 \times 10^{45}$. Assuming one

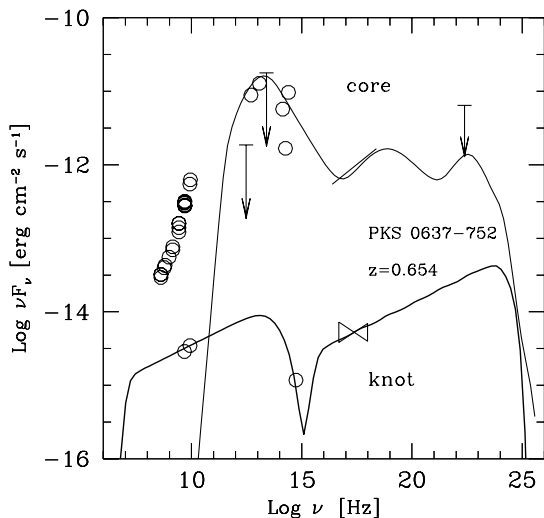


Figure 3. The SED of the core and of the extended 7.8" knot of the blazar PKS 0637-752. Data sources: NED for the core; Chartas et al. 2000 and Schwartz et al. 2000 for the knot in the jet. The solid lines are models calculated as explained in the text.

(cold) proton for each electron, the estimated kinetic power is of order $L_{\text{kin}} = 3 \times 10^{47} \text{ erg s}^{-1}$.

For the knot, we have assumed that the emission region has a size of $\sim 3 \text{ kpc}$, at a distance of 640 kpc from the center (corresponding to the deprojected observed distance, assuming a viewing angle of 6°). The magnetic field is $B = 6 \times 10^{-5} \text{ G}$, the intrinsic emitted luminosity is $L = 10^{41} \text{ erg s}^{-1}$ and the bulk Lorentz factor is $\Gamma_{\text{out}} = 14$. The viewing angle is the same as the core. With these parameters, the CMB contribution to the radiation fields as seen by the knot is largely dominating. At the redshift of PKS 0637-752 this corresponds to $U'_{\text{CMB}} \sim 6 \times 10^{-10} (\Gamma_{\text{out}}/14)^2 \text{ erg cm}^{-3}$, to be compared with $U'_B \sim 1.4 \times 10^{-10}$ and $U'_{\text{out}} \sim 2 \times 10^{-15} \text{ erg cm}^{-3}$. The jet kinetic powers in emitting electrons and in Poynting flux are respectively $L_e = 5 \times 10^{45}$ and $L_B = 2.6 \times 10^{47} \text{ erg s}^{-1}$. If there is one proton for emitting electron $L_{\text{kin}} = 4 \times 10^{47} \text{ erg s}^{-1}$. These numbers, typical for powerful radio sources, are in rough agreement with the corresponding values for the core, suggesting that the kinetic power is conserved along the jet (see e.g. Celotti & Fabian 1993).

The optical emission can be self-consistently interpreted as the higher energy part of the synchrotron component. This in turn implies that the emission is due to high energy electrons, whose cooling length corresponds to distances $\sim 0.5 \text{ kpc}$. Radio and X-ray emission are instead accounted for by particles of similar (lower) energies and therefore images in these two bands are expected to resemble each other (with cooling lengths $\sim 150 \text{ kpc}$), as indeed observed (Schwartz et al. 2000).

Finally note that the presence of a relativistically boosted component might also account for the otherwise unexplained X-ray (ROSAT HRI) emission of knots B and D in 3C 273, as recently reported by Röser et al. (2000).

5 DISCUSSION AND CONCLUSIONS

We have discussed the role of different electromagnetic fields for the radiative dissipation of relativistically accelerated electrons in large scale jets. The dissipation regions (knots) act as scattering mirrors for any externally produced photon field as well as the nuclear beamed radiation. A jet structure comprising components with different speeds can account for large scale emission in jets associated with both blazar and radio-galaxies.

In the former case, we expect to detect more intense radiation from a fast moving component (spine), spatially concentrated in the outer jet regions and dominated by the CMB scattered field at distances greater than a few kpc. On the contrary, weaker and more isotropic emission would dominate in radio-galaxies, produced by a mildly relativistic portion of the jet, mainly Compton scattering the beamed radiation coming from the nucleus. Deviation from this behavior in radio galaxies is expected for jets which are subject to strong bending: in this case the inner beamed field would not reach any misdirected component.

Interestingly, we predict jet/counterjet ratios in the range 4-20 even for the less beamed component. High contrast maps at high energies of both quasars and radio galaxies are thus crucial test for this scenario.

While the above estimates imply values of the kinetic power associated with the emitting knots typical of high power radio sources, a quasi-stationary hydrodynamical confinement of such structures appears to be a problem as extreme high gas densities for the external gas would be required.

We expect that optical and X-ray emission to be common in large scale jets of both blazar and radio-galaxies. The promising results by *Chandra* and HST will thus play a key role in the understanding of the jet structure and dynamics as well as the dissipation processes.

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